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**TEXTILE CAPACITOR PATENT: AFRL EARNS PATENT  
FOR AN AIRFRAME INTEGRATED ENERGY STORAGE  
TECHNOLOGY CONCEPT (PREPRINT)**

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Structures Division**

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14. ABSTRACT Three AFRL scientists, William Baron, Dr. Maxwell Blair, and Sandra Fries-Carr recently received a patent entitled "Airframe Structure-Integrated Capacitor." Structural capacitor implies that in addition to carrying load, the aircraft or spacecraft structure maintains capacitive charge for energy storage and power conditioning used in a variety of applications, both pulsed and continuous. The specific objectives of this effort are identifying a plausible design concept, conducting experimental trials, and characterizing the concept's structural and electrical efficiency. The concept is based on a dielectric-coated conductor with a conductive metal outerlayer, then integrate the coaxial system into a hybridized, composite weave with carbon tow for additional reinforcement.					
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AFRL scientists earn patent for an airframe integrated energy storage technology concept

Mr. William Baron and Ms. Melissa Withrow (Azimuth) of the Air Force Research Laboratory, Air Vehicles Directorate wrote this article.

The Air Force is evolving from a cold war era force with a large, containment focused infrastructure to a smaller, more responsive, and more affordable Expeditionary Aerospace Force (EAF) that is less vulnerable to loss. In support of this transformation, AFRL is developing affordable, sustainable, and scalable force applications like directed energy weapons, kinetic energy weapons, electromagnetic guns and launchers, and high-power microwaves.

Capacitors are an essential component in all of these systems because of their ability to store prime electrical energy and expel it in short, fast energy pulses. If made using conventional technology, the capacitors required to support these systems would be bulky and weigh thousands of pounds. However, AFRL researchers are exploring ways to integrate load bearing capacitor fibers into air vehicle structure to reduce airframe weight, free up valuable space, and offer fuel cost savings.

Three AFRL scientists, Mr. William Baron, Dr. Maxwell Blair, and Mrs. Sandra Fries-Carr recently received a patent entitled "Airframe Structure-Integrated Capacitor." Structural capacitor implies that in addition to carrying load, the aircraft or spacecraft structure maintains capacitive charge for energy storage and power conditioning used in a variety of applications, both pulsed and continuous. The specific objectives of this effort are identifying a plausible design concept, conducting experimental trials, and characterizing the concept's structural and electrical efficiency.

Of the capacitor types, the team considered only configurations capable of carrying normal, shear, and bending loads. Two common capacitors met this requirement: parallel plate capacitors and cylindrical capacitors. While evaluating parallel plate capacitors, researchers considered laminated structural systems of metal and dielectric material. They envisioned bonding sheets of aluminum to a dielectric material. Commercially available, structural precedents such as Arall™ use this procedure. While not being designed for electrical purposes, Arall™ is a structurally tough material constructed from impregnated aramid fibers bonded with aluminum sheets into a laminate. Technicians apply this design approach to the structural capacitor application by laminating a good dielectric with a conductive lamina. Because the parallel plate capacitor concept is quite efficient, it appeared to have significant potential. However, the team abandoned it because of the associated developmental challenges including controlling the dielectric layer properties, damage tolerance, and repair issues.

The team then focused on an alternative approach-- designing a cylindrical capacitor capable of reacting structural loads. Technicians would fabricate this concept by covering a dielectric-coated conductor with a conductive metal layer. Then, they would integrate the coaxial system into a hybridized, composite weave with carbon tow for additional reinforcement. Finally, they would lay up this material on a tool and infuse it with resin to



create an air vehicle's primary load-bearing structure. Capacitor performance is governed by dielectric characteristics, which are the Achilles heel of the electro-structural system. While the cylindrical capacitor approach allows for precise control over dielectric layer quality, it makes the energy's ingress to and egress from the structure much more complicated than the parallel plate solution. However, using the cylindrical capacitor composite allows engineers to integrate tens of thousands of feet of capacitor into air vehicle structure.

To demonstrate the basic concept, AFRL researchers used a commercially-available copper wire with Kapton™ dielectric, an aromatic polyimide material available in numerous manufactured product forms. Kapton™ material has voltage breakdown strengths of around 7000 KV/mil and offers low electromagnetic losses. While designers did not intend for this material to form the basis of a transitionable solution, it is capable of showing concept feasibility and establishing future research activity parameters. For the purposes of the initial feasibility investigation, technicians fabricated the first specimens with a conductive copper paint offering a uniform coat and good adhesion. The team conducted an initial capacitor test to investigate performance using a Hewlett Packard 4284A precision impedance meter. Results showed good capacitance, inductance, and resistance from 1KHz to 1MHz. These results were significant considering the limited time spent optimizing the system.

The team then integrated the design into an experimental piece of carbon fabric material, evaluated its ability to maintain structural capacitance, and showed the weaving process viability. This process required significant capacitive wire because one square foot of plain weave fabric requires 120 feet of cylindrical capacitor when used only in the fabric warp direction at 10 pics/inch. The team created a small, task-specific weaving machine to produce a structural capacitor fabric coupon measuring 8.0 inches wide by 14.0 inches long. Testing this specimen (shown in Figure 1) verified the capacitor concept's preliminary feasibility. Researchers used this demonstrated performance in an integrated conceptual air vehicle fuselage design resulting in 168.92  $\mu$ farads at high voltage.

In the future, superior dielectrics that offer improved structural and electric performance will increase the energy density the structures are capable of storing. The AFRL team has been working with researchers from the University of Dayton Research Institute (UDRI) to develop high performance resins for dielectric performance with good structural properties. This work has involved doping resins to improve the voltage breakdown strength, to provide low electromagnetic losses, and to increase the material dielectric constant. In addition, the team is developing material that is compatible with the structural resin infused into the panels and that has low moisture uptake characteristics because the dielectric will not be hermetically sealed. They are synthesizing this resin material so that it can be used in AFRL's precision dielectric coating pultrusion process currently being developed to produce the next generation of coaxial structural capacitors. A scanning electron microscope image of the doped resin is shown in Figure 2.

In addition, researchers have made significant progress in lowering the structural capacitor concept's specific weight and improving its durability. The first improvement was



eliminating the copper paint electrode. This step involved considering several options, including metal foil bonding, electro-less plating, metal coating flame spray, vapor deposition, and braiding a conductive surface with composite fibers. For the second generation device, researchers used a conductive fiber over-braid to improve structural and electrical performance. They have tested several variations of this over-braid including braids fabricated from Titanium, Copper Zirconium alloy, and carbon tow. These braids provided an overall thickness of approximately 4 mils, so they could be integrated into the composite architecture with a small profile. Researchers evaluated these materials based on cost, electrical resistance, weight, and ease of fabrication. Based on these factors, they chose the carbon braid electrode shown in Figure 3 for future development activity. They also evaluated copper zirconium options for the center electrode. The zirconium in the copper improved the structural fatigue resistance with minimal impact on the electrical conductivity. However, the desire to further reduce weight has inspired current, additional efforts to fabricate the center electrode using carbon fiber tow in a pultrusion process.

Finally, researchers used the Textile Composite Analysis for Design (TEXCAD) computer program to model the plain weave unit cell structure used in the feasibility work. TEXCAD is a general-purpose micromechanics code that models yarn architecture to predict three-dimensional thermal and mechanical properties, damage initiation and progression, strength under tension, compression, and shear. These analyses guided development of an advanced textile architecture and resulted in a new weave that provided significant fiber volume fraction increase and improved weight efficiency. Researchers then modeled this new weave with the UDRI team using a novel finite element approach in the ABAQUS finite element analysis software suite that uses embedded elements. These elements made possible detailed modeling of the complex architecture. This modeling has established mechanical performance estimates that will be used to baseline empirical results and update vehicle conceptual design application studies. In addition, AFRL has accomplished preliminary analyses characterizing the Lorentz forces induced during structural capacitor system discharge. These forces arise from the electrostatic and electromagnetic fields and can induce significant mechanical stresses in the dielectric layers. Parametric studies have characterized the physical and operational effects on the stress levels induced into the dielectric material.

The team has developed several approaches to demonstrate bussing energy into and out of the structure. These approaches include various attempts at designing an integrated buss structure that transfers critical loads through joints to prevent disrupting the load path. Alternative concepts involve beaming loads around dielectrically isolated buss structures, which are integrated into the load bearing panels. Technicians have fabricated prototype panels to validate these approaches. Researchers are using the results to optimize structural performance and develop improved fabrication methods and buss integration designs. It is likely that implementing this technology in the future will involve integrating an active switching network into the buss system. This type of network would allow creation of parallel networks of series circuits to provide power handling tailored to weapon system requirements. Another advantage of this network is that if any load bearing capacitor elements shorted due to in service structural damage, the active network could eliminate those components from the circuit.

Developing this technology is an important step for fulfilling future Air Force needs. One day, engineers will use capabilities developed by AFRL researchers to design smaller air vehicles able to deliver short pulses of electrical energy to energize directed energy weapons to provide necessary power for air vehicle subsystems. These air vehicles will play an important role in the future Air Force and will forever change the face of warfare.